Fundamental Parameters of the Standard Model

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Particle Physics

Standard Model

19 Parameters

- Gauge couplings: α_s, α_{QED}, $\alpha_W = (m_W/v)^2/\pi$;
- Lepton masses: m_e, m_μ, m_τ;
- Quark masses: $m_u e^{i\theta}$, m_d, m_s, m_c, m_b, m_t;
- CKM: V_{us}, V_{cb}, V_{ub}, $\sin\delta_{KM}$;
- EWSB: $v = 246$ GeV, $\lambda = (m_H/v)^2/2$.
- Need lattice QCD, lattice Yukawa.

Existential Questions

- What breaks electroweak symmetry?
- What generates flavor? Flavor change V?
- Why is $m_u < m_d$? Is $m_u = 0$?
- With δ_{KM} (and θ), what causes *CP* violation?
- Without these, no chemistry or biology.

- Most particle physicists believe that the answers lie beyond the SM:
  - model-building theorists;
  - experimenters searching.
- To recognize BSM, need precision SM.
- Half the parameters are “obscured” by nonperturbative QCD: need lattice QCD.
- (And who says EWSB is weakly coupled?)

SM Status

- Gauge symmetry
- Quantum numbers
- Higgs sector
- $\boxed{\text{Flavor interactions}}$

- Law of Nature
- Law of Nature
- Speculation
- $\boxed{\text{Testable science}}$

Lattice QCD Data

Asqtad Data Mine

MILC + USQCD

(2002–2009)

$a = 0.18$ fm not
$a = 0.15$ fm shown

am_l / am_s	$m_\pi L$	Lattice	# Lats
$a = 0.12$ fm			
0.40/0.40	29.4	$20^3 \times 64$	332
0.20/0.20	19.6	$20^3 \times 64$	341
0.10/0.10	13.7	$20^3 \times 64$	339
0.05/0.05	9.7	$20^3 \times 64$	425
0.04/0.05	8.7	$20^3 \times 64$	351
0.03 / 0.05	7.6	$20^3 \times 64$	564
0.02 / 0.05	6.2	$20^3 \times 64$	1758E
0.01 / 0.05	4.5	$20^3 \times 64$	2023E
0.01 / 0.05	6.3	$28^3 \times 64$	241
0.007 / 0.05	3.8	$20^3 \times 64$	1852E
0.005 / 0.05	3.8	$24^3 \times 64$	1802E
0.03 / 0.03	7.6	$20^3 \times 64$	359
0.01 / 0.03	4.5	$20^3 \times 64$	346

am_l / am_s	$m_\pi L$	Lattice	# Lats
$a \approx 0.09$ fm			
0.0124 / 0.031	5.78	$28^3 \times 96$	1996C
0.0093 / 0.031	5.04	$28^3 \times 96$	1138C
0.0062 / 0.031	4.14	$28^3 \times 96$	1946C
0.00465 / 0.031	4.11	$32^3 \times 96$	540C
0.0031 / 0.031	4.21	$40^3 \times 96$	1012C
0.00155 / 0.031	4.80	$64^3 \times 96$	700R
0.0062 / 0.0186	4.09	$28^3 \times 96$	985C
0.0031 / 0.0186	4.22	$40^3 \times 96$	642N
0.0031 / 0.0031	4.20	$40^3 \times 96$	440R
$a \approx 0.06$ fm			
0.0072 / 0.018	6.33	$48^3 \times 144$	625
0.0054 / 0.018	5.48	$48^3 \times 144$	617C
0.0036 / 0.018	4.49	$48^3 \times 144$	771
0.0025 / 0.018	4.39	$56^3 \times 144$	800N
0.0018 / 0.018	4.27	$64^3 \times 144$	826C
0.0036 / 0.0108	5.96	$64^3 \times 144$	483N
$a \approx 0.045$ fm			
0.0028 / 0.0140	4.56	$64^3 \times 192$	861N

DWF Data Mine

RBC+UKQCD using resources of
RBRC, UKQCD, USQCD

2006

2007

2008

2009

a (fm)	volume	am_l/am_s	$m_\pi L$	lgfs
0.114	24^3x64	0.03/0.04	9.0	~200
		0.02/0.04	7.6	~200
		0.01/0.04	5.7	~800
		0.005/0.04	4.5	~800
0.081	32^3x64	0.008/0.03	5.5	~600
		0.006/0.03	4.8	~900
		0.004/0.03	4.0	~800

Non-US Data Mines

- MILC $n_f = 2{+}1$ ensembles most extensive anywhere.
- CP-PACS/PACS-CS and BMW ensembles ≈ RBC-UKQCD, but focus on masses, f_K/f_π.
- ETM $n_f = 2$ ensembles: serious SM pheno starting (but need extra error estimate).
- CLS plans set of $n_f = 2$ ensembles.

- All results presented here obtained from USQCD data mines, because:
  - LQCD Project under review today;
  - non-US SM calculations lag (either $n_f \leq 2$ or not written up).
- All “USQCD” data mines generated partly outside LQCD project: NSF, pre-LQCD; RBRC, UKQCD; DOE leadership class.

QCD Parameters

Quark Masses

- Light quark masses [arXiv:0903.3598+refs]:

$$
\begin{aligned}
m_u/m_d &= 0.42 \pm 0_{\rm stat} \pm 0.01_{\rm syst} \pm 0.04_{\rm EM} \\
m_s/\hat{m} &= 27.2 \pm 0.1_{\rm stat} \pm 0.3_{\rm syst} \pm 0_{\rm EM} \\
\bar{m}_s(2\ \mathrm{GeV}) &= 88 \pm 0_{\rm stat} \pm 3_{\rm syst} \pm 0_{\rm EM} \pm 4_{\rm match}\ \mathrm{MeV}
\end{aligned}
$$

  with two-loop matching [hep-lat/0511160].

- Tom Banks: Really?! We have to stop hoping that $m_u = 0$? Are others checking this?

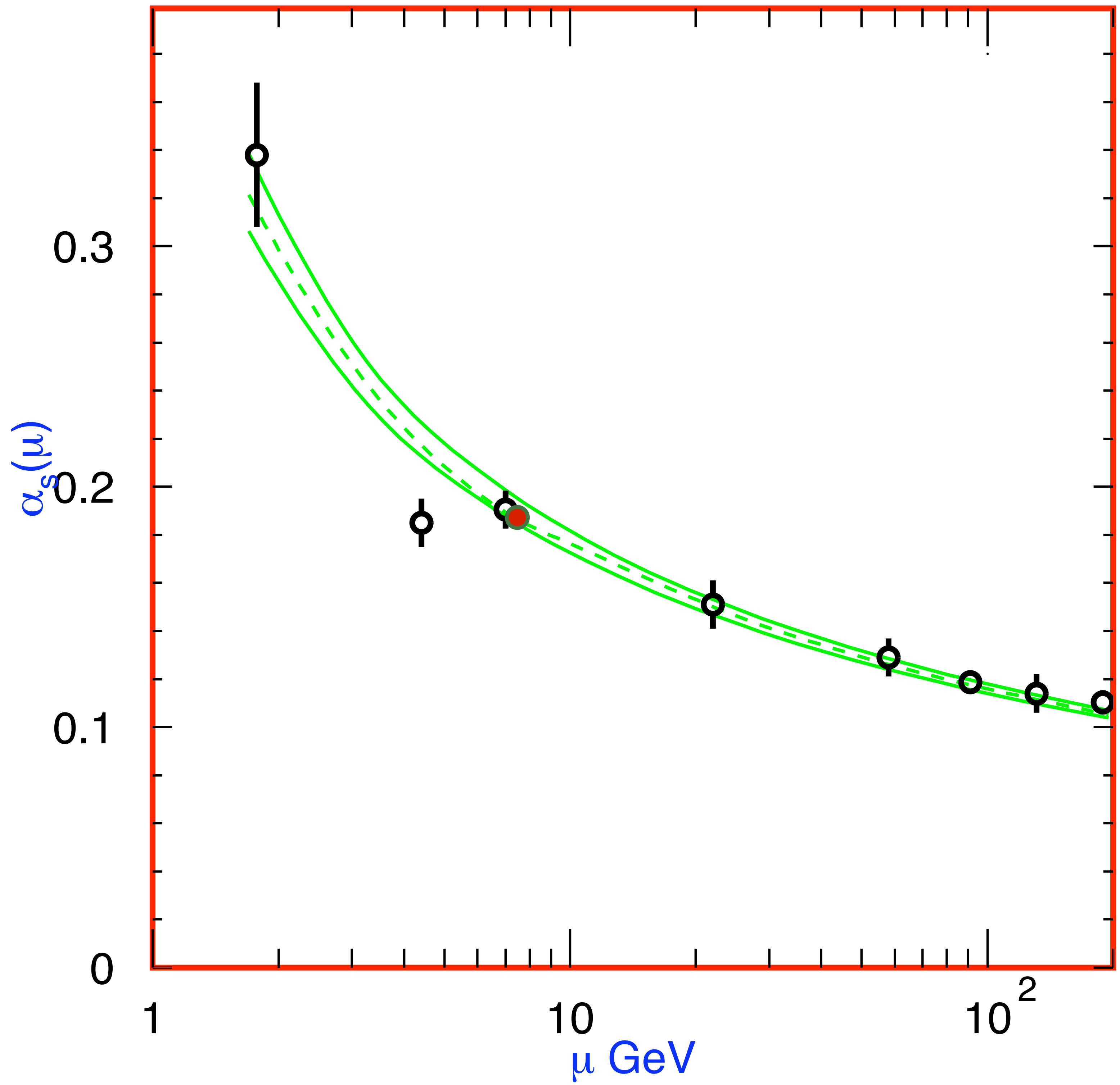
- RBC/UKQCD checking; Sharpe non-pert Z_m.

- Charmed quark mass [on 2+1 asqtad sea]:
  - charmonium correlators from HPQCD;
  - α_s^3 PT by Karlsruhe.
- Similar to Karlsruhe analysis of e^+e^- data.
- Results:
  - $m_c(m_c)$ = 1.268(9) GeV [HPQCD lattice],
  - $m_c(m_c)$ = 1.268(12) GeV [e^+e^- data].

Strong Coupling α_s

- Charmonium moments [arXiv:0805.2999]:
  - $\alpha_s = 0.1174(12)$.
- Wilson loops [on 2+1 asqtad sea]:
  - $\alpha_s = 0.1183(8)$, HPQCD, arXiv:0807.1687;
  - $\alpha_s = 0.1192(11)$, Maltman, arXiv:0807.2020;
- PDG non-lat average (2008): $\alpha_s = 0.1185(9)$.

PDG 2008



QCD of hadrons = QCD of partons

Flavor Physics

Flavor Physics

- The Cabibbo-Kobayashi-Maskawa matrix is special unitary, arising from diagonalization of Yukawa couplings. SU(3): 8 parameters.
- Symmetry of gauge interactions reduces CKM parameters to 4.
- Many testable constraints.

Assuming the SM:

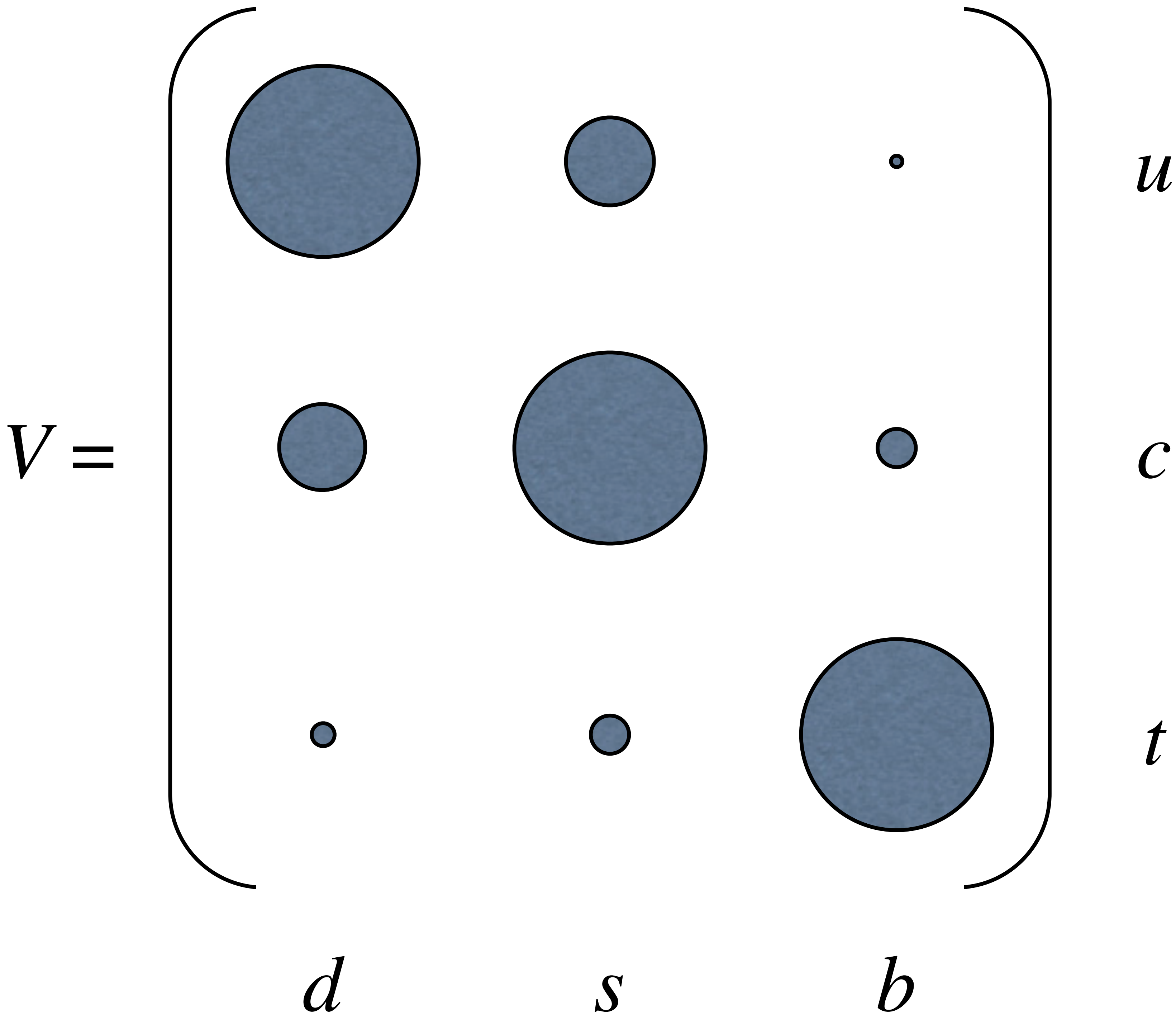
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \text{nuke } 0^+ \to 0^+ & K^+ \to \ell^+\nu & B \to \pi\ell\nu \\ \pi^+ \to \pi^0 e^+ \nu & K \to \pi\ell\nu & b \to u\ell\nu \\ V_{cd} & V_{cs} & V_{cb} \\ D \to \pi\ell\nu & D \to K\ell\nu & B \to D^*\ell\nu \\ D^+ \to \ell^+\nu & D_s \to \ell^+\nu & B \to D\ell\nu \\ V_{td} & V_{ts} & V_{tb} \\ B_d^0 \leftrightarrow \bar{B}_d^0 & B_s^0 \leftrightarrow \bar{B}_s^0 & t \to Wb,\ Wb \to t \end{pmatrix}$$

trees

loops

no go

CKM Hierarchy



Measuring CKM

- For numerous processes:

$$\Gamma = \begin{pmatrix} \text{known} \\ \text{factors} \end{pmatrix} \begin{pmatrix} \text{CKM} \\ \text{factors} \end{pmatrix} \begin{pmatrix} \text{QCD} \\ \text{factor} \end{pmatrix}$$

- Decay constants, bag factors, form factors.
- Leptonic decays, meson mixing, semileptonic.

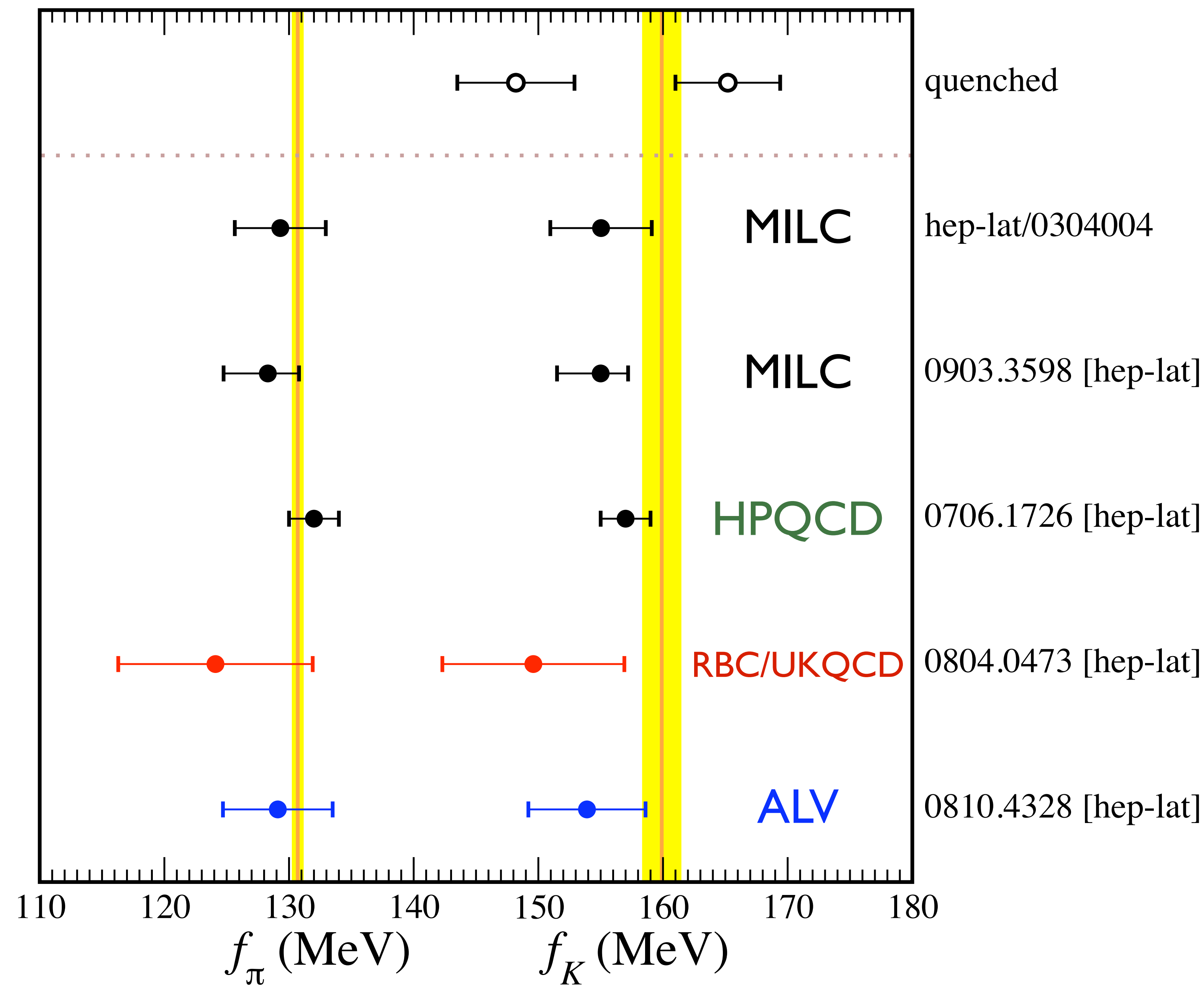
Decay Constants

- One of the simplest quantities is decay constant of pseudoscalar mesons, f_π, *etc*.
- Some results (entries in MeV):

meson	MILC	FNAL	HPQCD	Expt	Dev (σ)
π	128 ± 3	—	132 ± 2	130.7 ± 0.4	0.4
K	155 ± 3	—	157 ± 2	159.9 ± 1.5	1.7
D	—	207 ± 11	207 ± 4	206 ± 9	0.1
D_s	—	249 ± 11	241 ± 3	263.1 ± 6.7	3.0

f_π and f_K

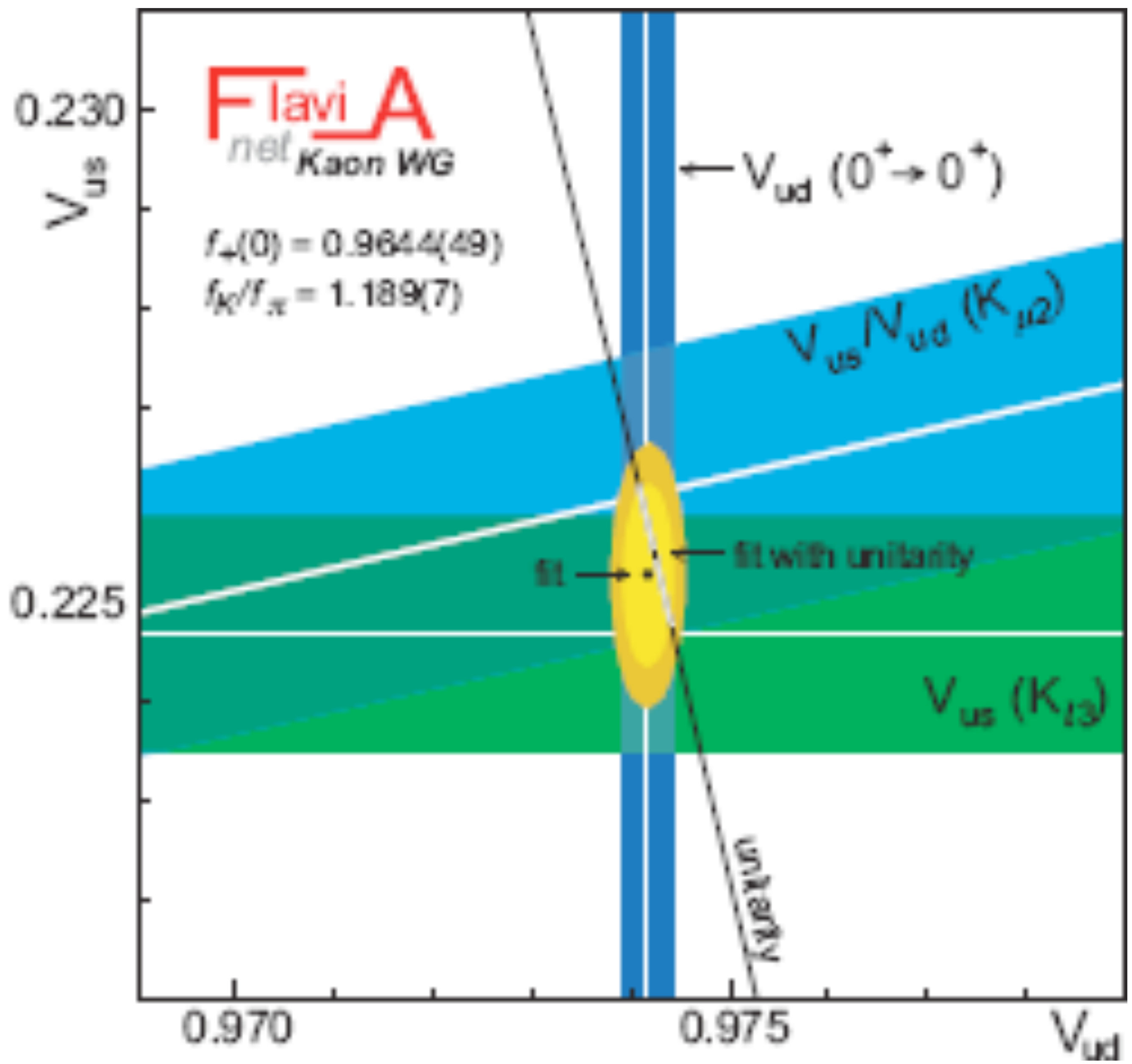
- Reproducible:
  - Asqtad on asqtad
  - HISQ on asqtad
  - DWF on DWF
  - DWF on asqtad
- Others have f_K/f_π.
- Solidification.



$|V_{us}|$

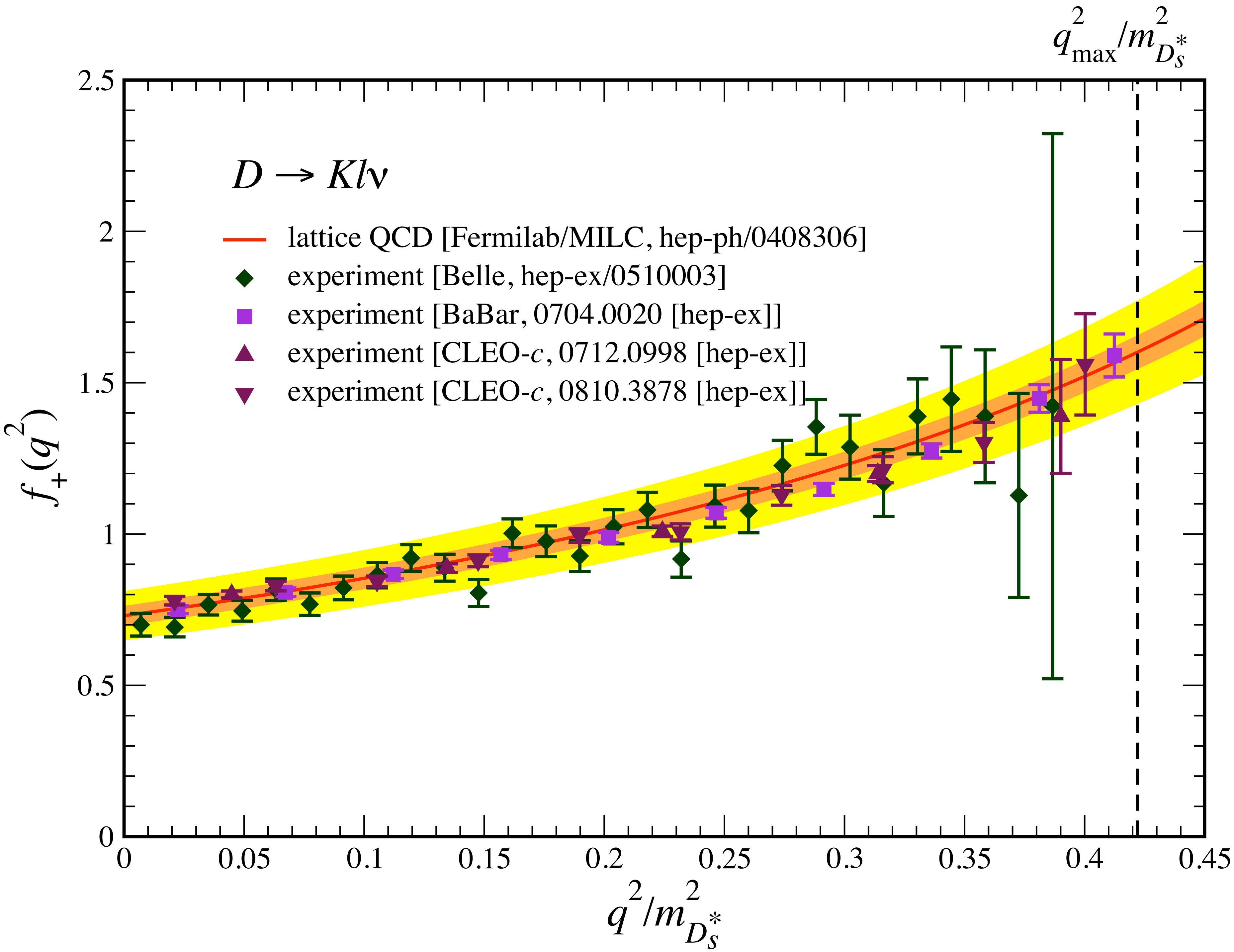
Flavianet Kaon WG: http://ific.uv.es/flavianet/

- V_{ud} from nuclear
- $f_+(0)$ from arXiv: 0710.5136 [RBC/UKQCD]
- f_K/f_π from arXiv: 0706.1726 [HPQCD]

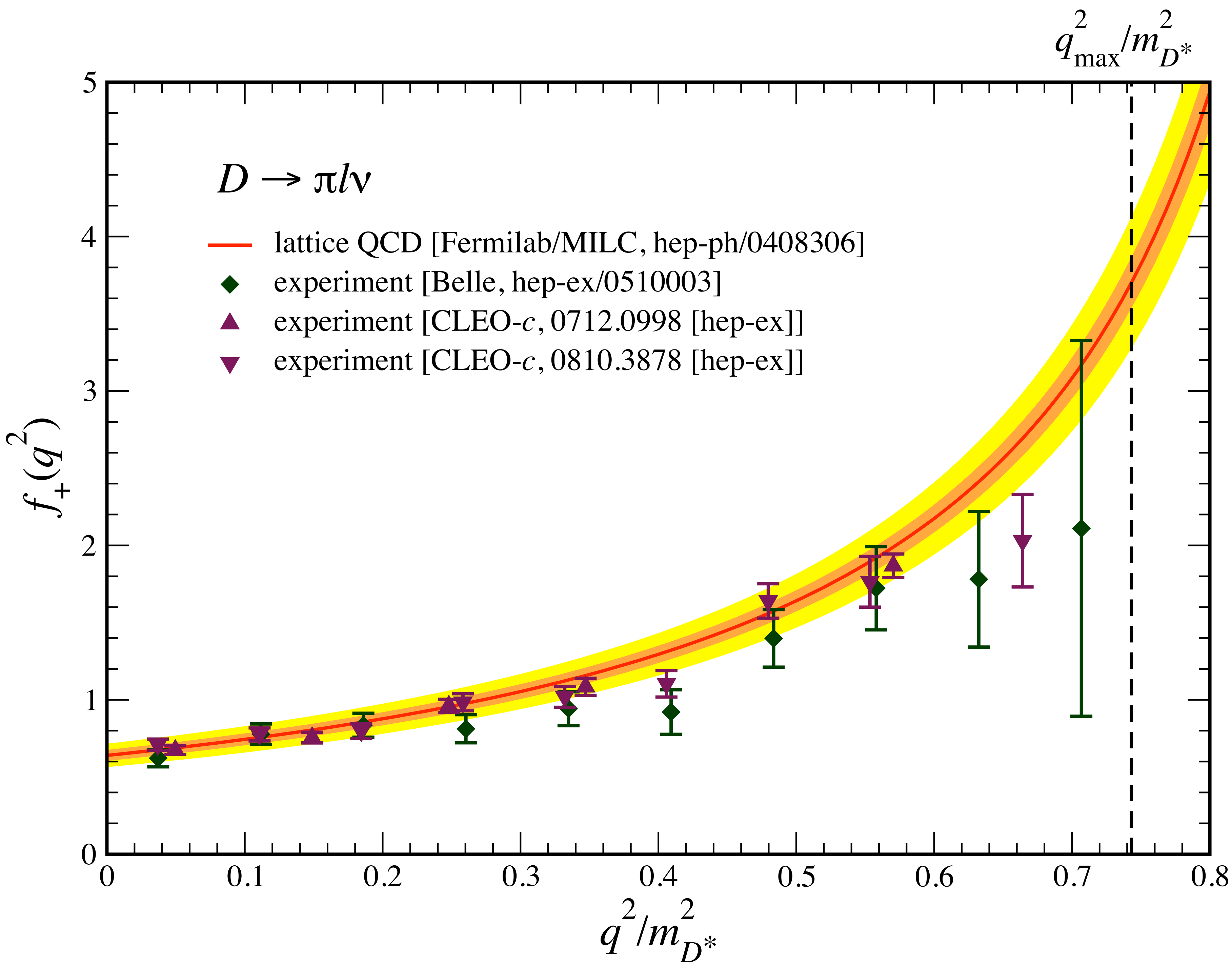


D Meson Decays

- Taking $|V_{ud}|$ & $|V_{us}|$ and CKM unitarity yields $|V_{cs}|$ & $|V_{cd}|$ (with sub per cent error).
- With this step, leptonic & semileptonic decays of *D* and D_s mesons are known ...
  - ... up to decay constants and form factors, calculable with lattice QCD.



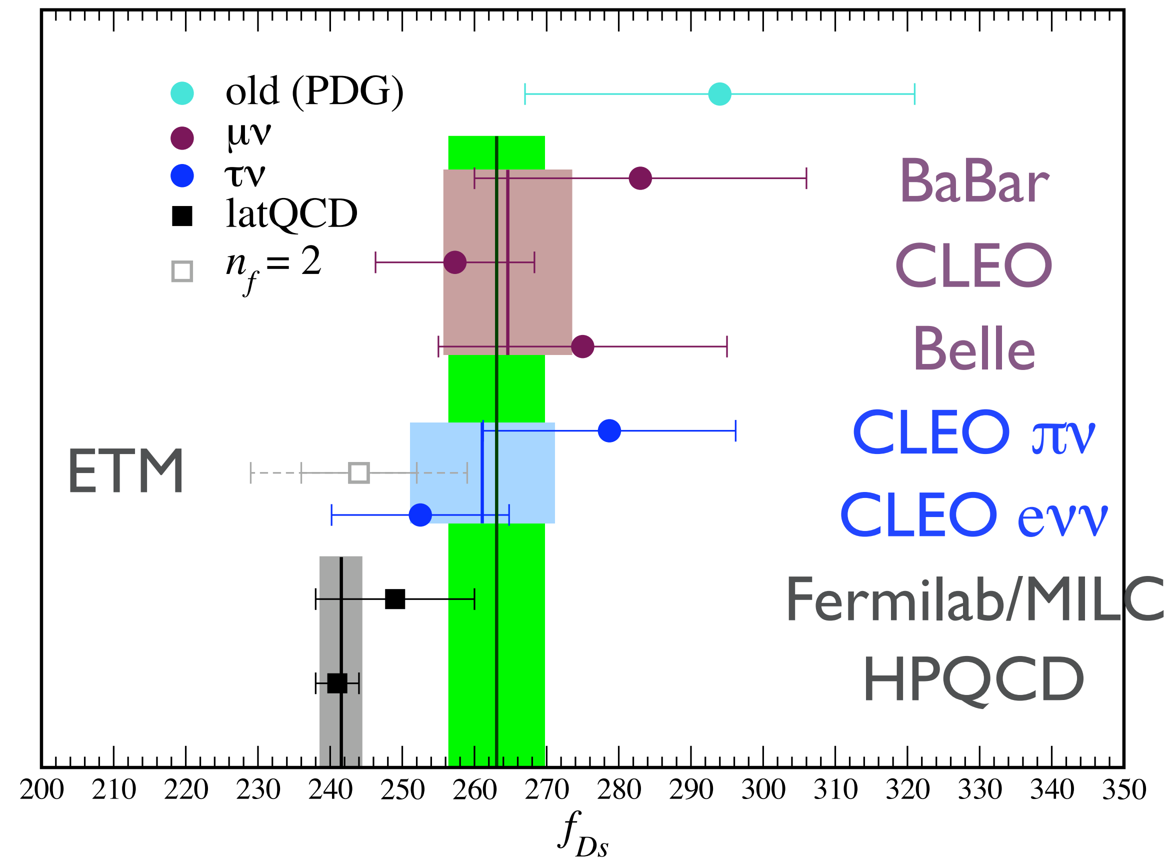
Plot prepared for a paper supporting CLEO's 500th paper of all time.

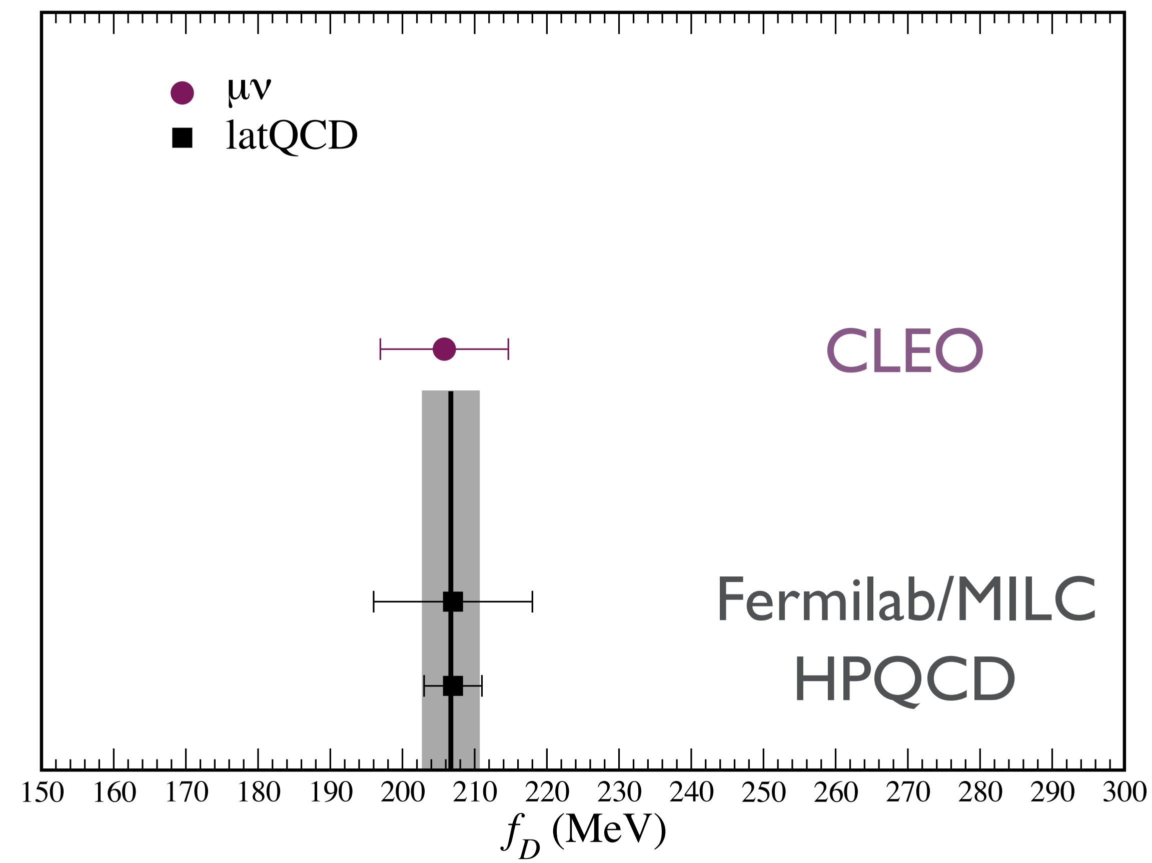


More precise measurements to appear in CLEO's 500th paper.

D_s Puzzle

- 0σ for $D \to l\nu$.
- 3σ for $D_s \to l\nu$:
  - exptl statistical σ.
- Can't blame it on charm.
- If new physics, then leptoquarks.
- BaBar remeasuring.





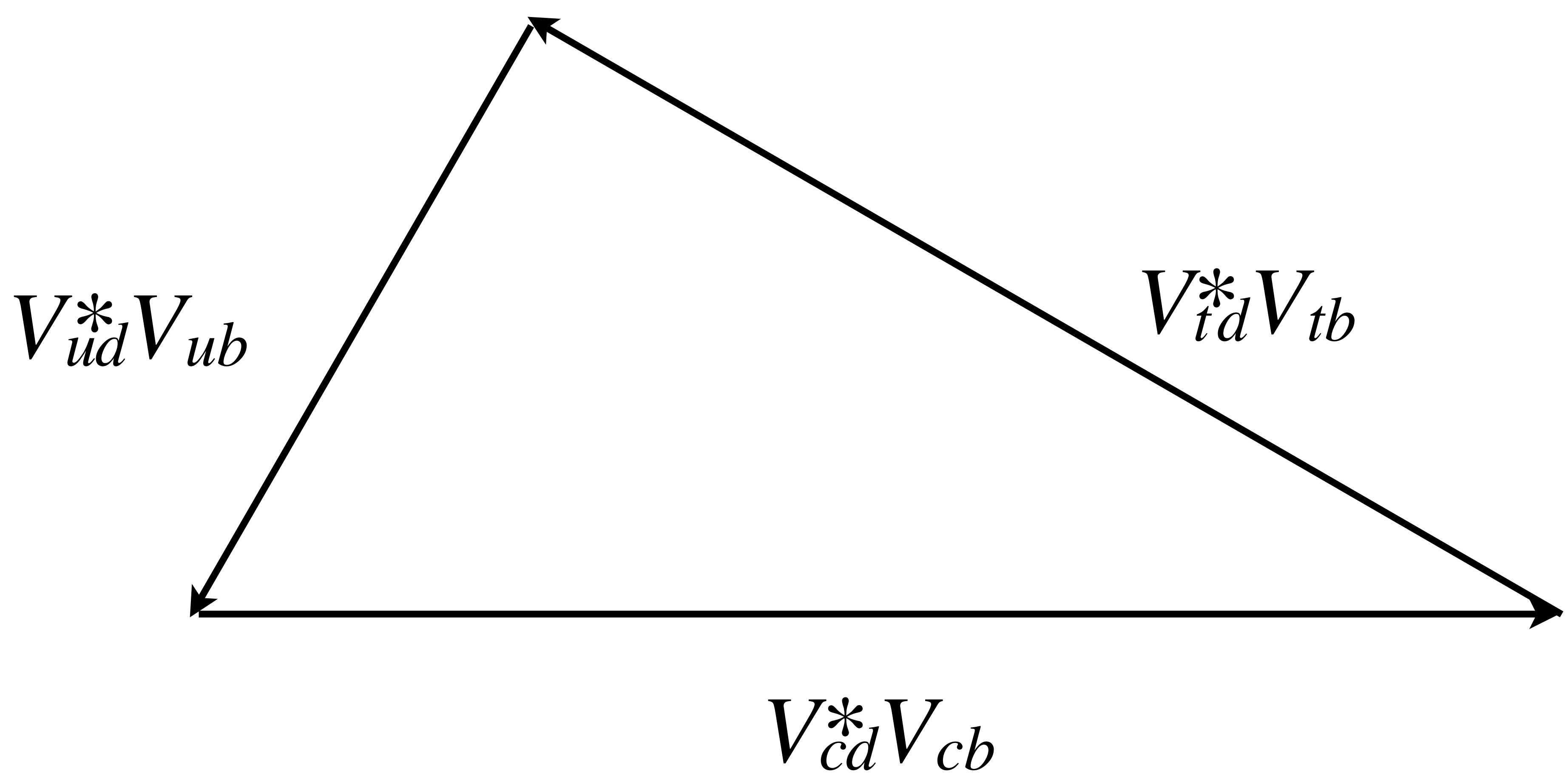
Unitarity Triangle

- Dozens of measurements, but unitarity of CKM constrains SM predictions:

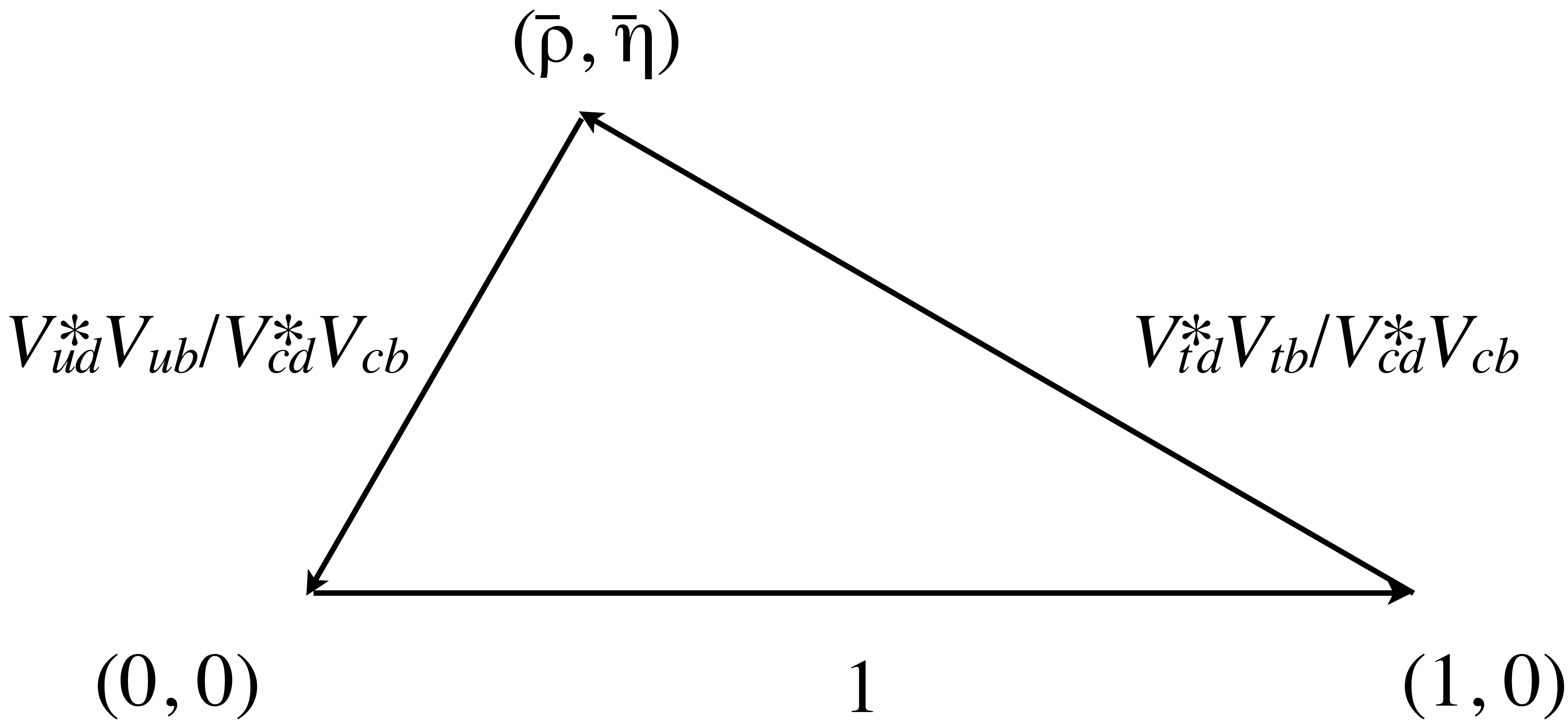
$$V_{ud}^{*}V_{ub} + V_{cd}^{*}V_{cb} + V_{td}^{*}V_{tb} = 0$$

  tracing out a triangle on complex plane.

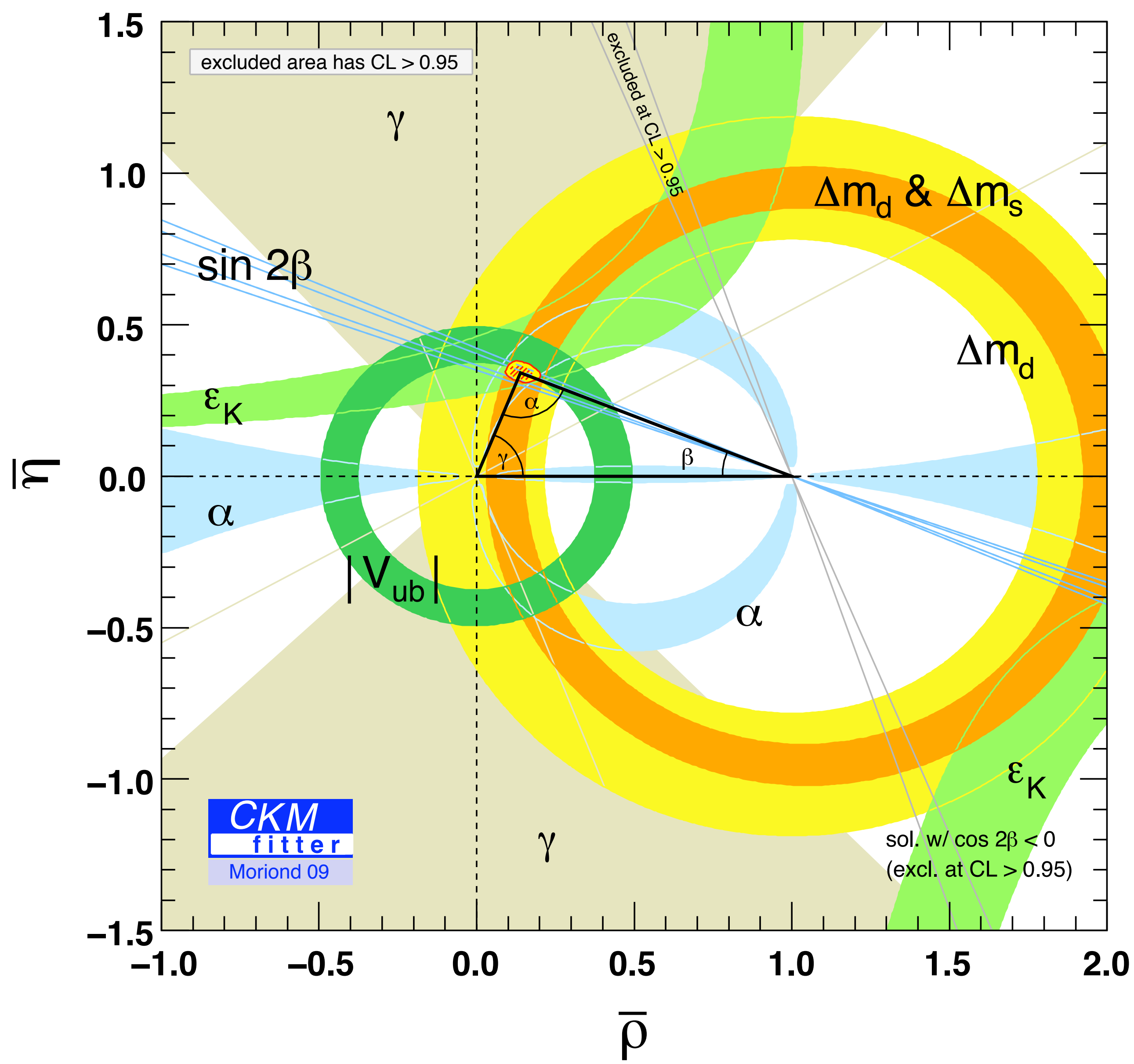
- Results often summarized with this so-called unitarity triangle.

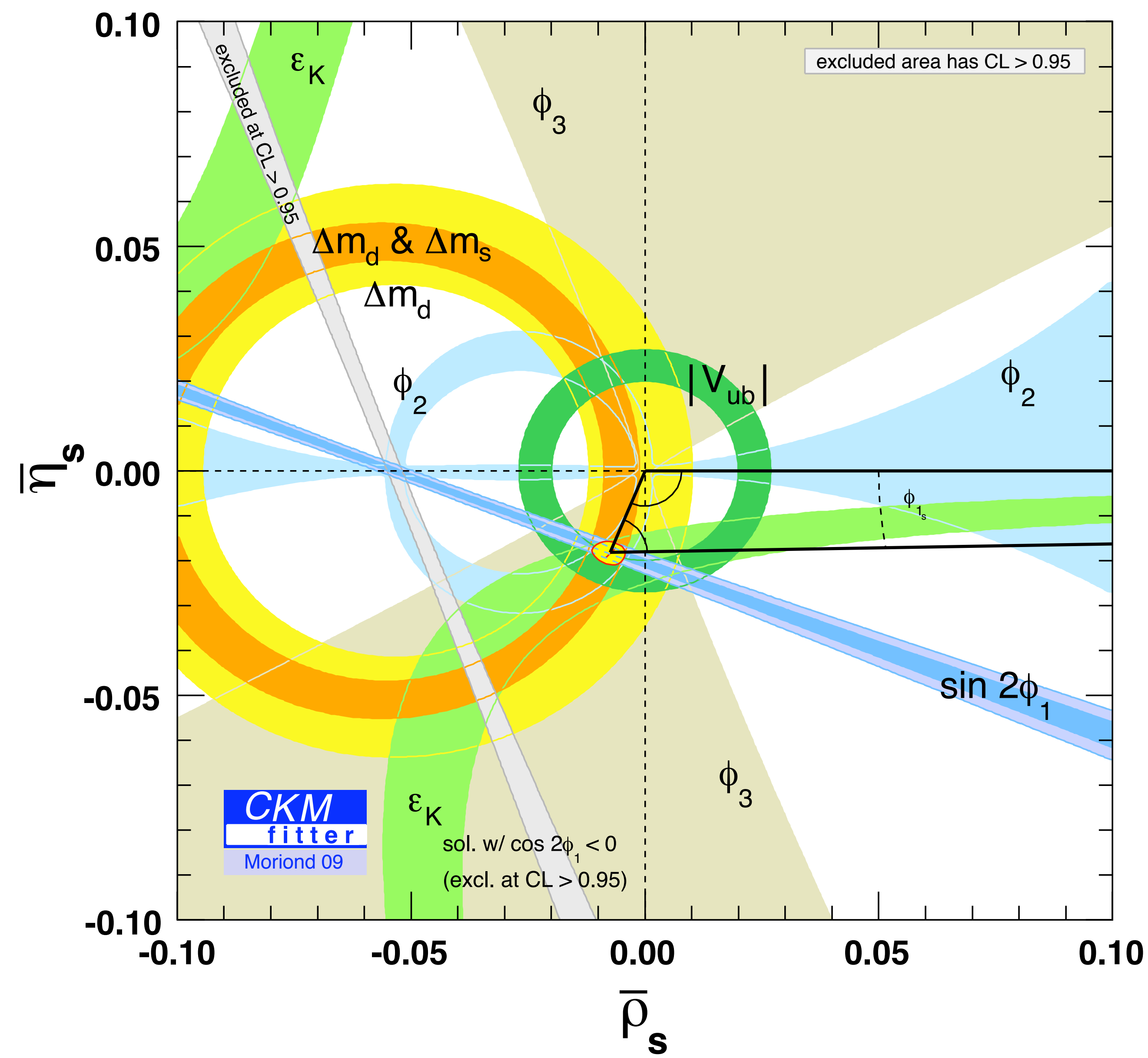

$V_{ud}^* V_{ub}$
$V_{td}^* V_{tb}$
$V_{cd}^* V_{cb}$

Unitarity Triangle



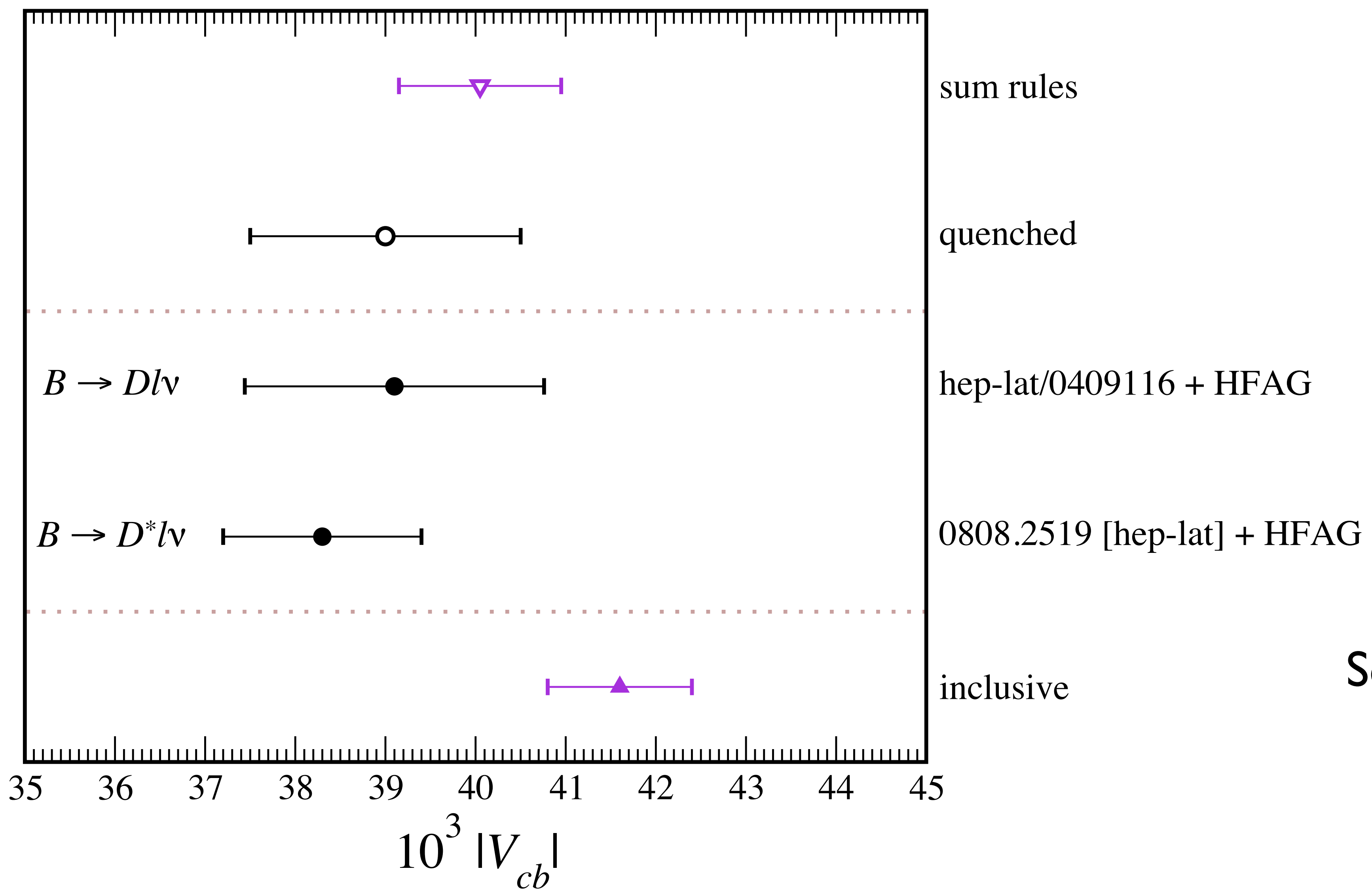
CKM UT Now





$$(\beta, \alpha, \gamma) = (\phi_1, \phi_2, \phi_3)$$

$|V_{cb}|$ normalizes UT

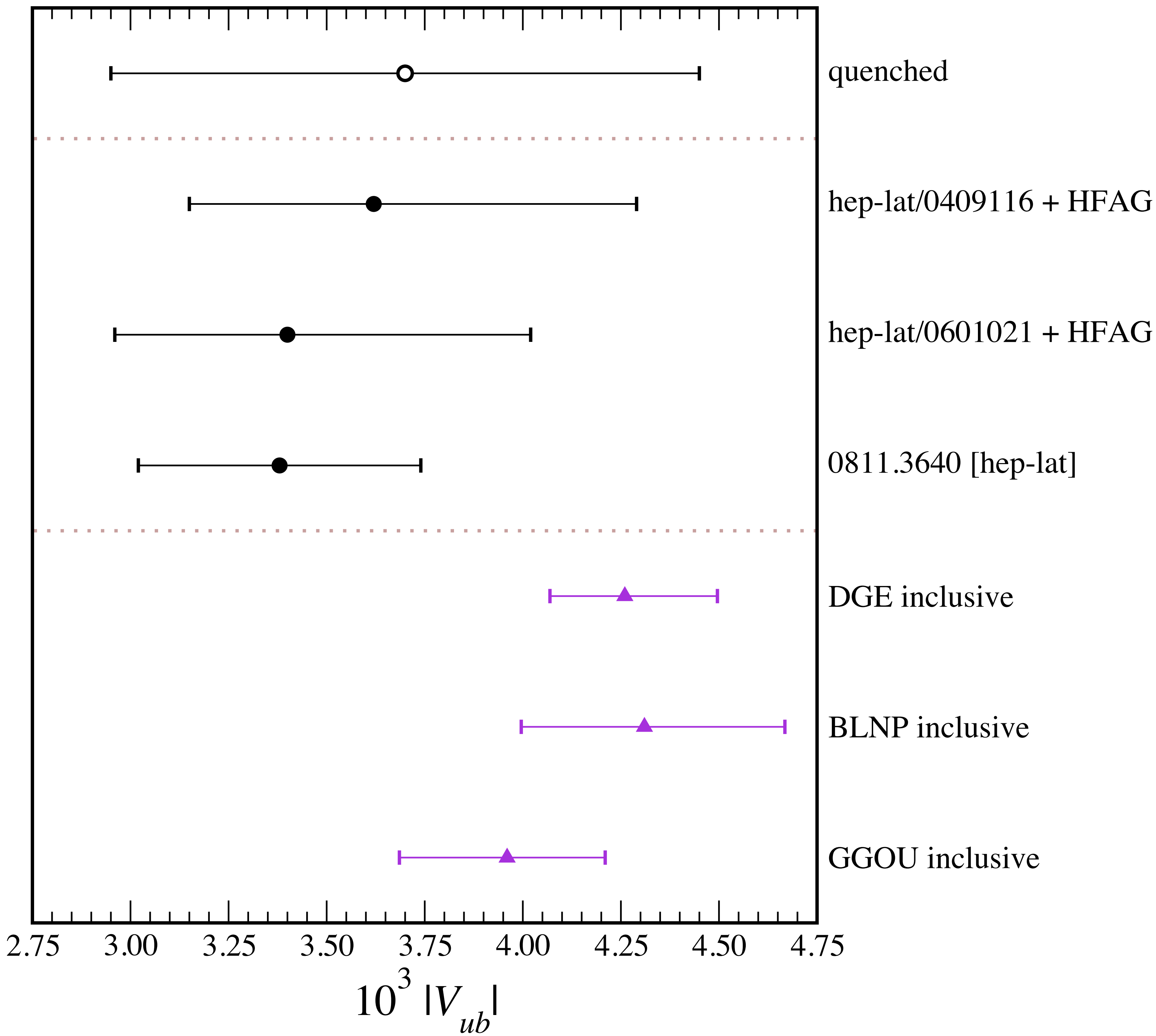


Fermilab/MILC

Fermilab/MILC

Schwanda at FPCP

Christoph Schwanda (at CKM): 2.5σ tension, so examine correlations in inputs to inclusive.



$|V_{ub}|$

Fermilab/MILC

HPQCD

Fermilab/MILC

$$\sigma_{\mathrm{th}} \approx \sqrt{2}\sigma_{\mathrm{expt}}$$

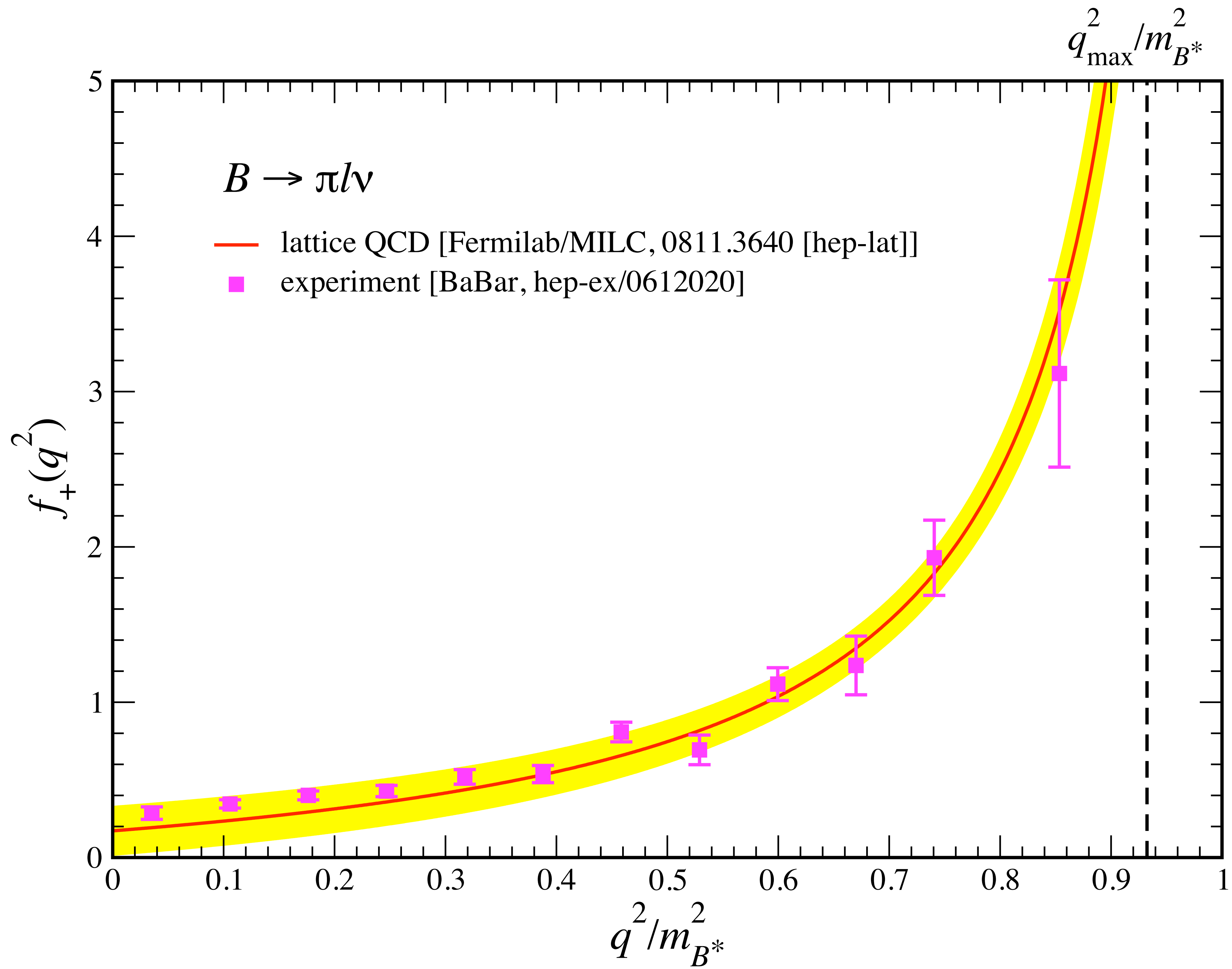
Paolo Gambino (at La Thuile): Tension!
New physics, like LR models?

- The most recent work on $B \to \pi l \nu$ makes noteworthy use of experimental data.

- Separately fit *shape* of lattice QCD $f_+(q^2)$ and BaBar's $|V_{ub}|f_+(q^2)$.

- Shapes agree, so proceed to combined fit: relative normalization is $|V_{ub}|$.

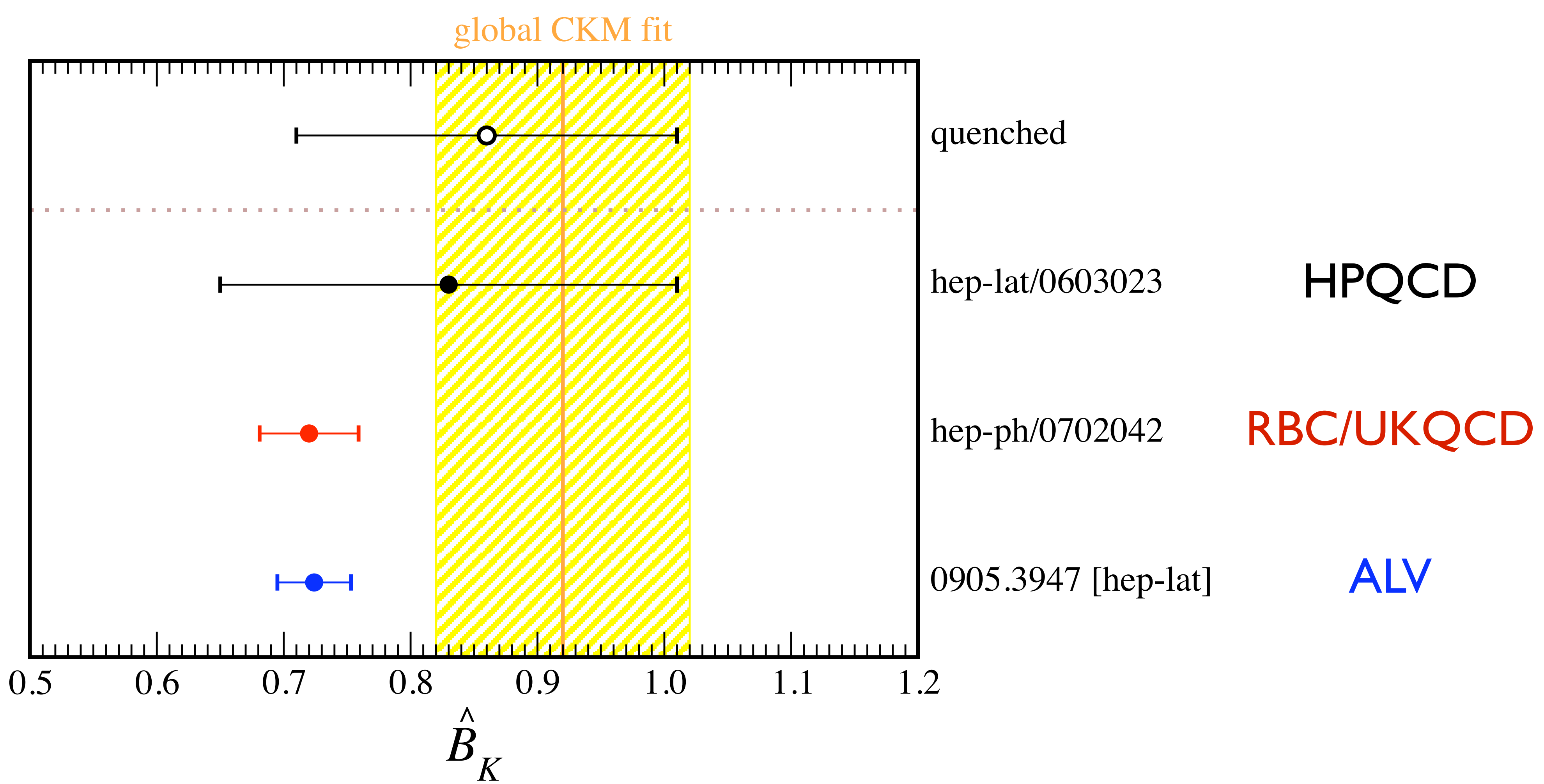
- Finds optimal combo of lattice, expt errors.



Curve: convergent z fit of lattice QCD

Points: BaBar data scaled by final $|V_{ub}|$

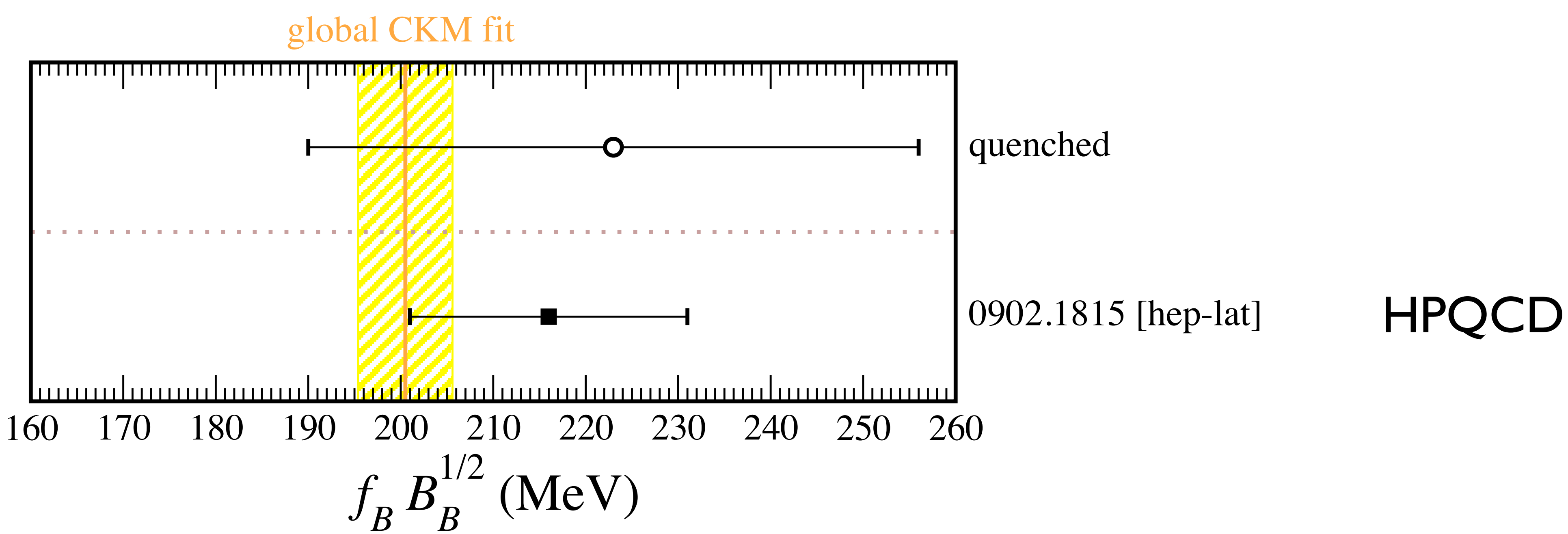
sin δ_{KM} via Kaon Mixing



Note tension between direct (i.e., lattice) and indirect view of kaon mixing [e.g., Lunghi, Soni].

$|V_{td}|$ & $|V_{ts}|$

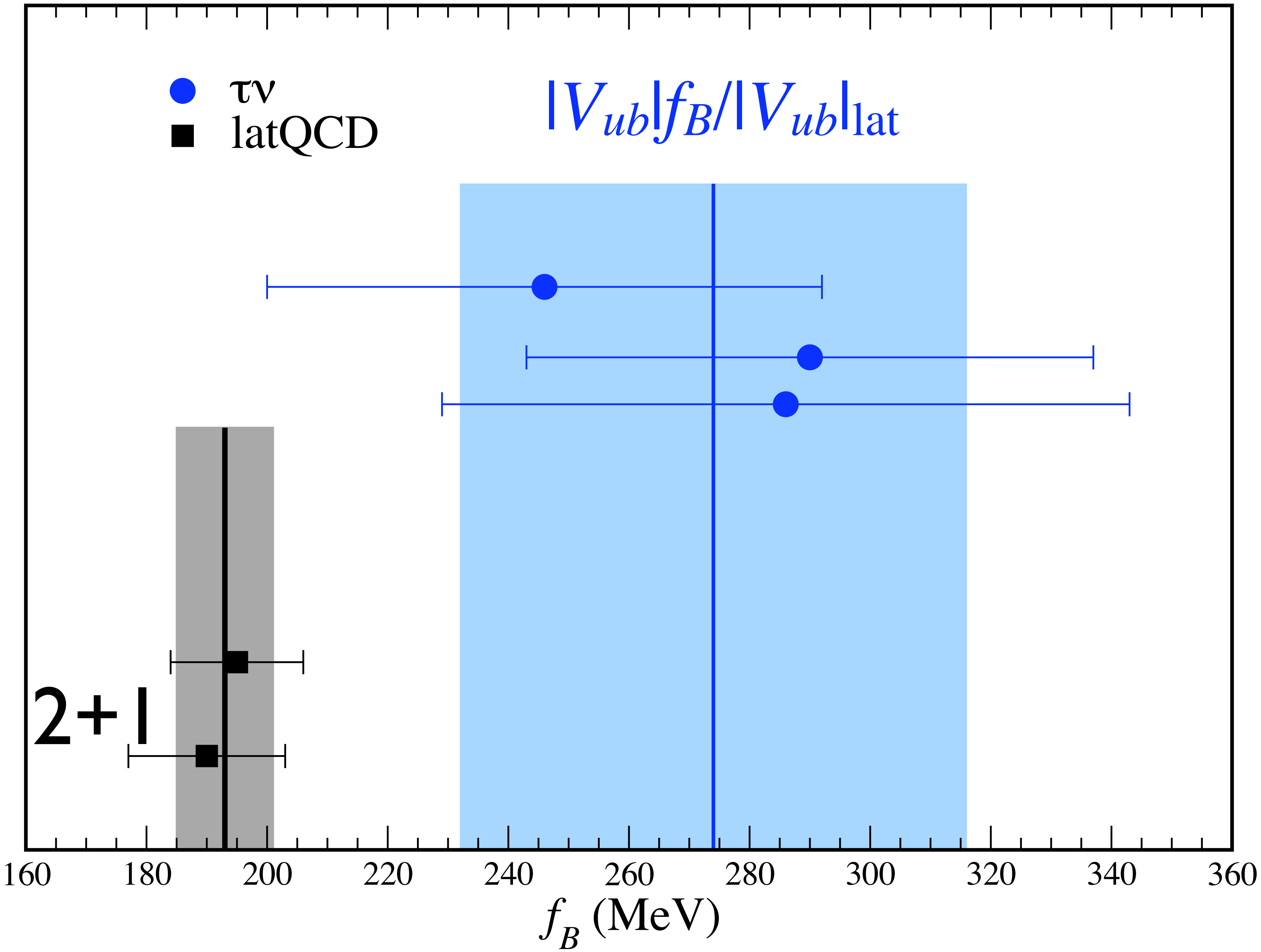
- *B* meson mixing is sensitive to top quark.
- Experiments <1% precision, for *B*, B_s.
- Four-quark operators; operator mixing.



$B \to \tau\nu$

- Assuming the SM, $|V_{ub}|f_B = 0.925 \pm 0.101$ MeV.
- With $|V_{ub}|$ from the exclusive method, this implies $f_B = 274 \pm 42$ MeV.
- Rather higher than LQCD avg: $f_B = 193 \pm 8$ MeV [HPQCD $\oplus$ Fermilab/MILC]
- What could explain the discrepancy?
    - A non-Standard charged particle, recently observed (in the theoretical literature).

A graphical view:



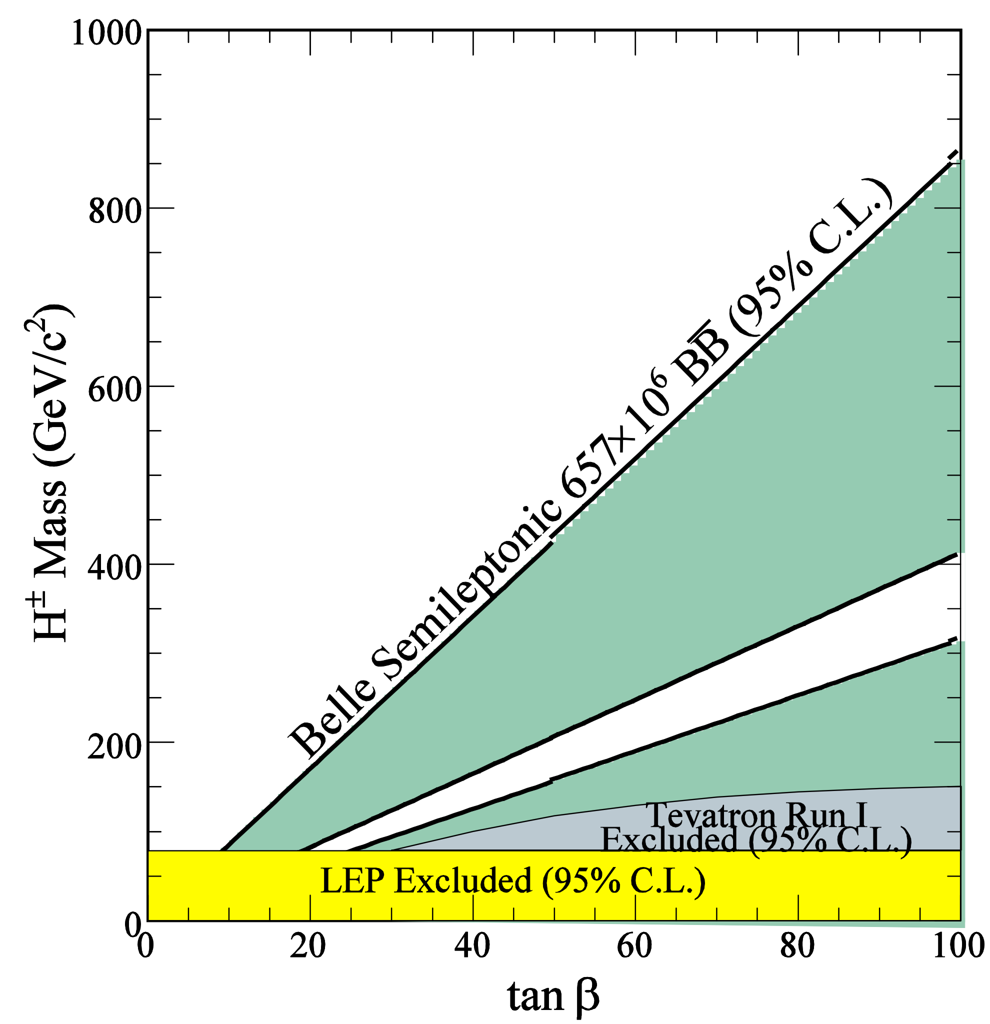
BaBar
Belle

Fermilab/MILC
HPQCD

a 1.9σ discrepancy.

Exclusion Plot

- Charged Higgs: multiply BR with $[1 - \tan^2\beta\,(m_B/m_H)^2]^2$
- Exclude part of $(\tan\beta, m_H)$ plane.
- Non-standard $H^\pm$ overwhelms $W^\pm$.



Perspective

Outlook

- Lattice QCD shaping HEP's perspective on α_s, quark masses, and flavor physics:
  - in some cases with no alternative.
- Still, however, at the beginning: LQCD precision lags experiment on f_π, f_K, meson mixing, and semileptonic form factors.

- At the outset of the LQCD Project, the USQCD Collaboration forecast the reduction in errors with LQCD resources.

  - A Case Study of the Impact of Increased Computational Resources on Lattice Gauge Theory Calculation: Constraints on Standard Model Parameters

- Key results (B_K, $f_B B_B^{1/2}$, ξ, $|V_{cb}|$ & $|V_{ub}|$) shown here have all met these aspirations.

- Experiments involved:
  - Kaon: E865, ISTRA+, KLOE, KTeV, NA48.
  - Charm: FOCUS, CLEO-c, Belle, BaBar.
  - *B*: BaBar, Belle, CLEO, CDF, D0.
  - Future: rare *K*, BES-3, LHC-b, ATLAS, CMS, super *B* factories.

Questions?